The Necessity of DUNE Intranuclear $\mathcal{B}-\mathcal{L}$-Violating Searches for a World-Leading, Complementary Physics Program

by J. L. Barrow

Snowmass Neutrino Frontier:
Beyond Standard Model (NF03) Kickoff Meeting
September 17th, 2020

Please see the associated Letter of Interest, and references therein

THE UNIVERSITY OF TENNESSEE KNOXVILLE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITIES RESEARCH ASSOCIATION

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Theoretical Points

Why $\mathcal{B} - \mathcal{L}$ Violation?

How do we understand baryogenesis?

SCIENCE AND TECHNOLOGY

Astrophysicists prove Big Bang was result of gender reveal party gone wrong

1 WEEK AGO *by* MARY GILLIS [@LIVING_MARBLE]

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Can $\Delta B = \Delta L$ Remedy the Baryon Asymmetry?

- Baryon (B) and lepton number (L) are violated ***infinitesimally*** in the SM due to anomalies
- The SM nonperturbatively conserves $B - L$ (t'Hooft 1976)

$$\Longrightarrow \Delta B = \Delta L$$

- It turns out that no theory that operates within the SM has produced a proper baryon abundance ***yet, fully and consistently—EWBG???***
  - **Topological tunneling** is completely ***inadequate***
  - The **sphaleron** mechanism still ***washes out*** any asymmetry we would see today ***if*** when they are generated they conserve $B - L$

A. D. Dolgov, *Baryogenesis, 30 Years Later*
M. E. Shaposhnikov et al 1993 and 1998

Figure 1
correspo

The short answer?

NO!

Proceed by contradiction…

SHOULD

$$B - L$$

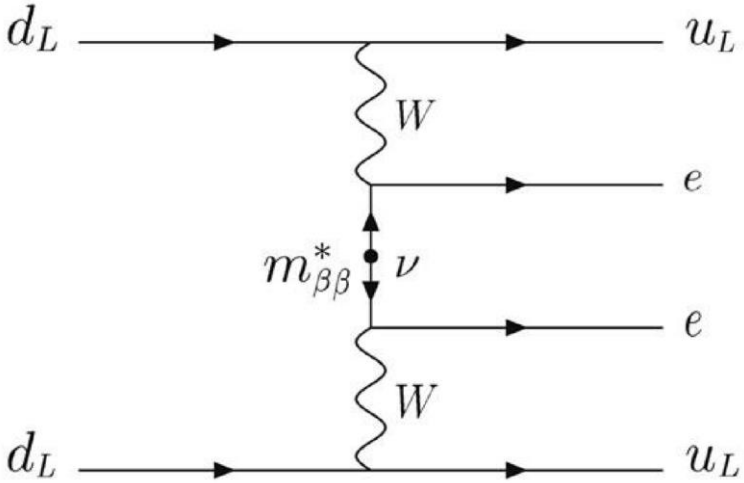
BE VIOLATED???

Maybe…

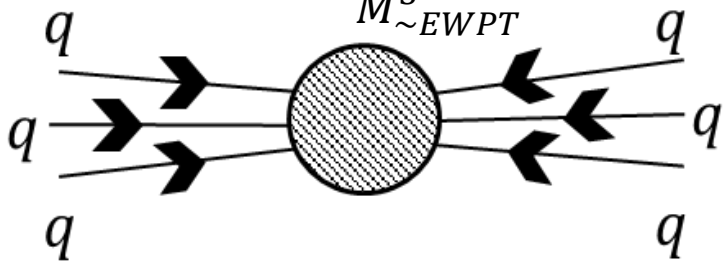
But let's be more *conservative*, and focus on observing processes with

$$\Delta B \neq 0$$

Going Beyond the Standard Model



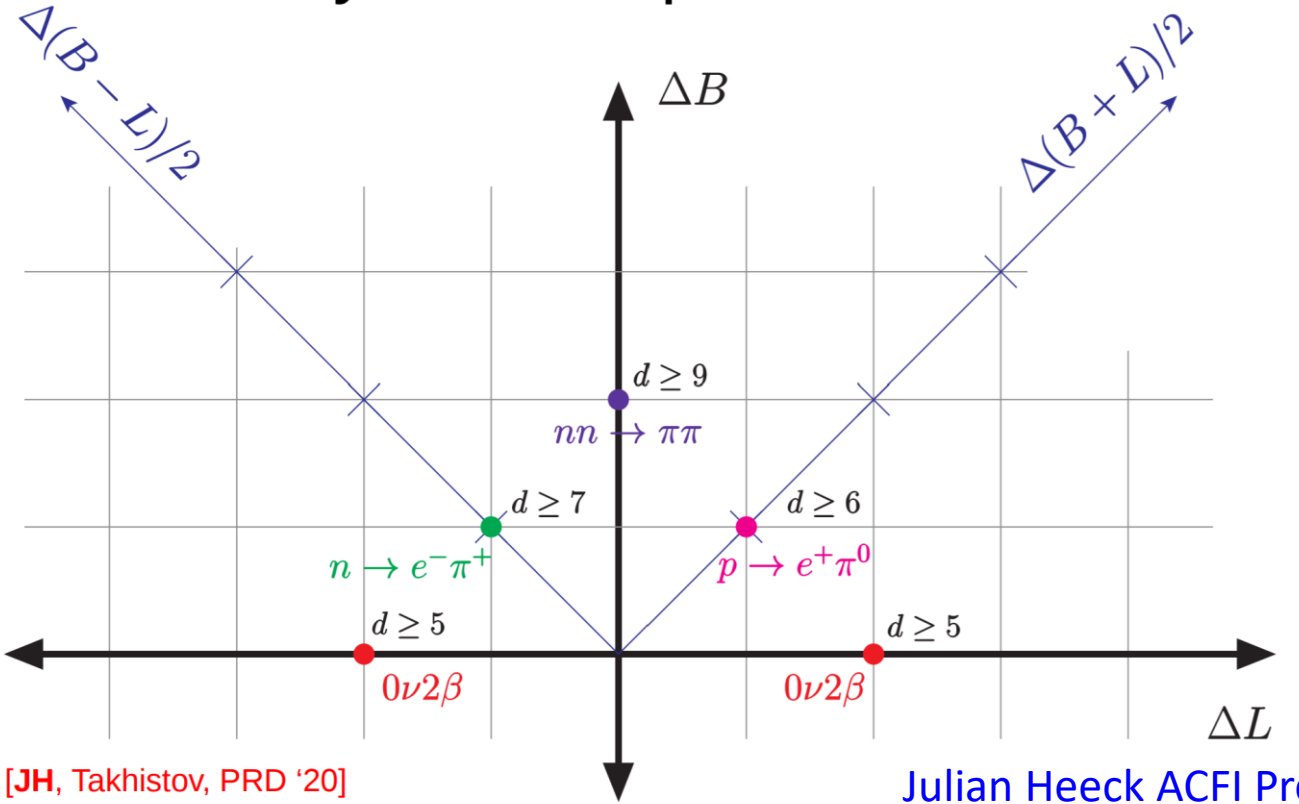
$$\mathcal{O}^9_{2\mathrm{N}} \sim \lambda \frac{qqq\bar{q}\bar{q}\bar{q}}{M^5_{\sim EWPT}}$$



What else do we need to add?

- Proton decay? $\propto qqql \Longrightarrow B - L$ conserving
  - Important to some BSM GUT SUSY theories
  - No experimental evidence in large volume detectors
  - LHC has turned up no persistent signs of SUSY
- Some other kinds of $\Delta B \neq 0$ or $\Delta L \neq 0$?
  - $\boldsymbol{\Delta B = 2}$ operators?
  - $\boldsymbol{\Delta L = 2}$ $\Longrightarrow$leptogenesis?
- Why some over others?
  - ***Can they properly generate the baryon asymmetry of the universe?***
  - ***At what energy scales can these theoretically produce the correct value?***

Baryon and lepton number

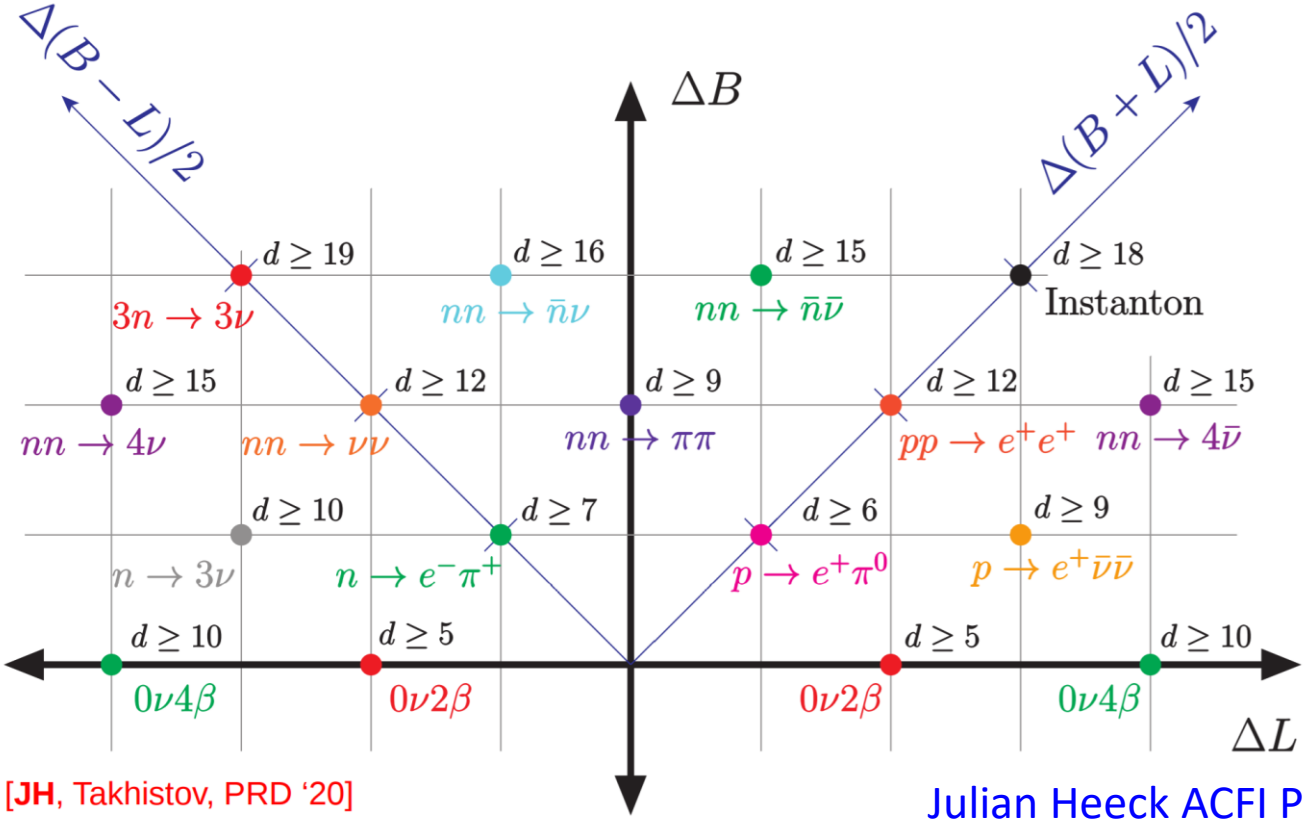


[**JH**, Takhistov, PRD '20]

[Julian Heeck ACFI Presentation]

ACFI, 8/6/20 Julian Heeck 7

Exotic ΔB and ΔL



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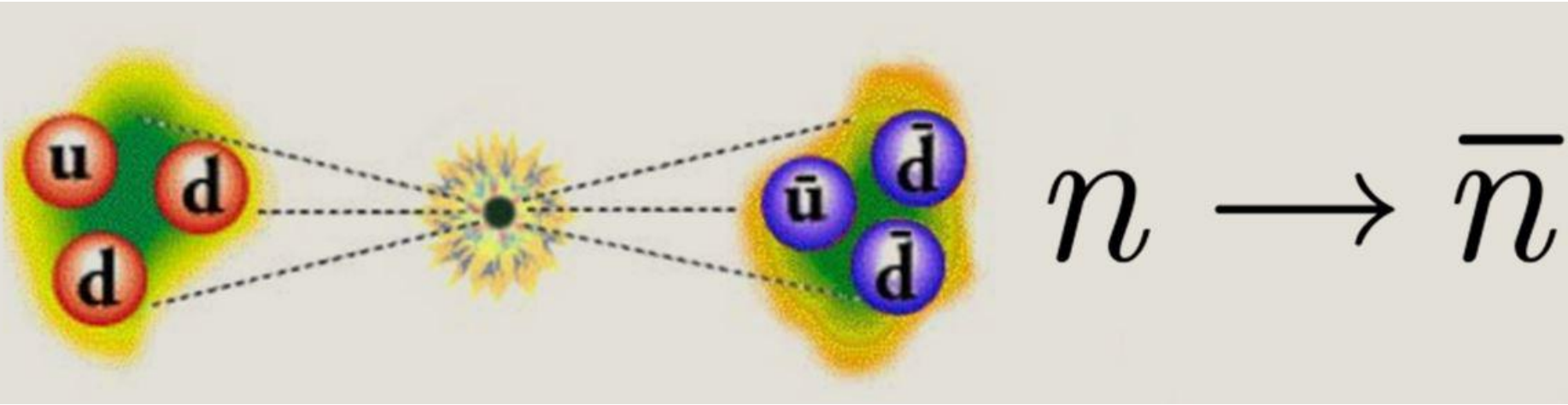


A Few (MC Truth) Considerations

Toward the Future

Consider $\mathcal{B} - \mathcal{L}$-violating $n \to \bar{n}$

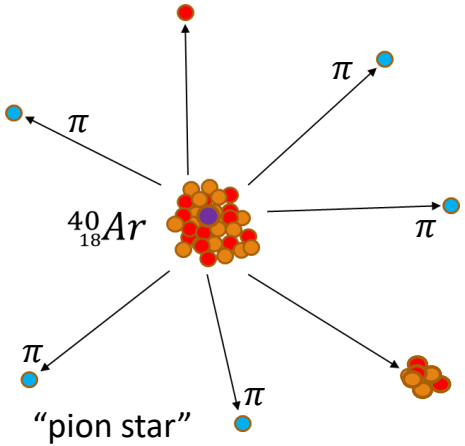
Understanding Modeling Systematics Beyond Previous Ad-hoc Assumptions

Signal Comparison

$n \to \bar{n}$ vs. Backgrounds (ex: Atmospheric Neutrino, ν)

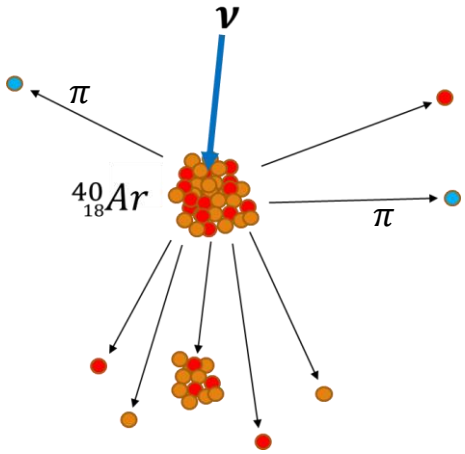
Dover, Gal, and Richard 1983, 1985, ***and*** 1996
~Golubeva and Kondratyuk, 1997
Kopeliovich et al 2018
Golubeva, JB, Ladd 2019
JB, Golubeva, Richard, Paryev 2020

- $n \to \bar{n}$ Annihilation and Knockouts



- ~Noncontinuous energy spectrum
- Generally a ~spherical topology
- ~Low momentum due only to Fermi motion

- Neutral Current Atmospheric ν



- Continuous energy spectrum
- Generally a ~correlated topology
- Large range of total momentum

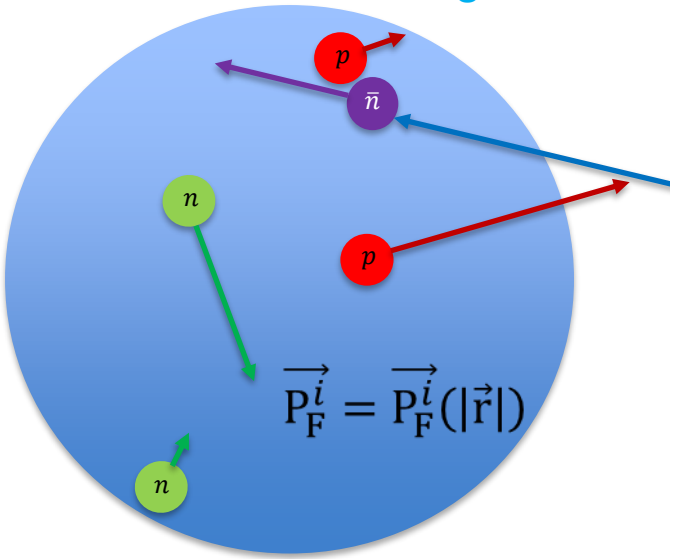
- Antineutron
- Neutron
- Proton
- Pion

Goals of Ongoing Studies

- Utilize realistic models of rare process signals and associated backgrounds
  - Integration of the newest ***nuclear model configurations*** available in `GENIE` ***and other $n \rightarrow \bar{n}$ generators from Golubeva et al.*** into full DUNE reconstruction chain underway
  - Fully oscillated atmospheric neutrino fluxes/spectra; expected counts complete
  - Proper ν_τ CC-interactions ***and subsequent τ decays underway*** (issues with GEANT)
- Approximate uncertainties in signal and background topologies
  - Iterate across many nuclear model configurations ***and generators*** as possible
- Automate analysis techniques to extract expected lower limits of many rare processes
  - ***Generate many different samples for many different signals over many different nuclear model configurations, producing outputs from many individually trained CNN/BDTs***

The Importance of *Some* Initial Physical Correlations

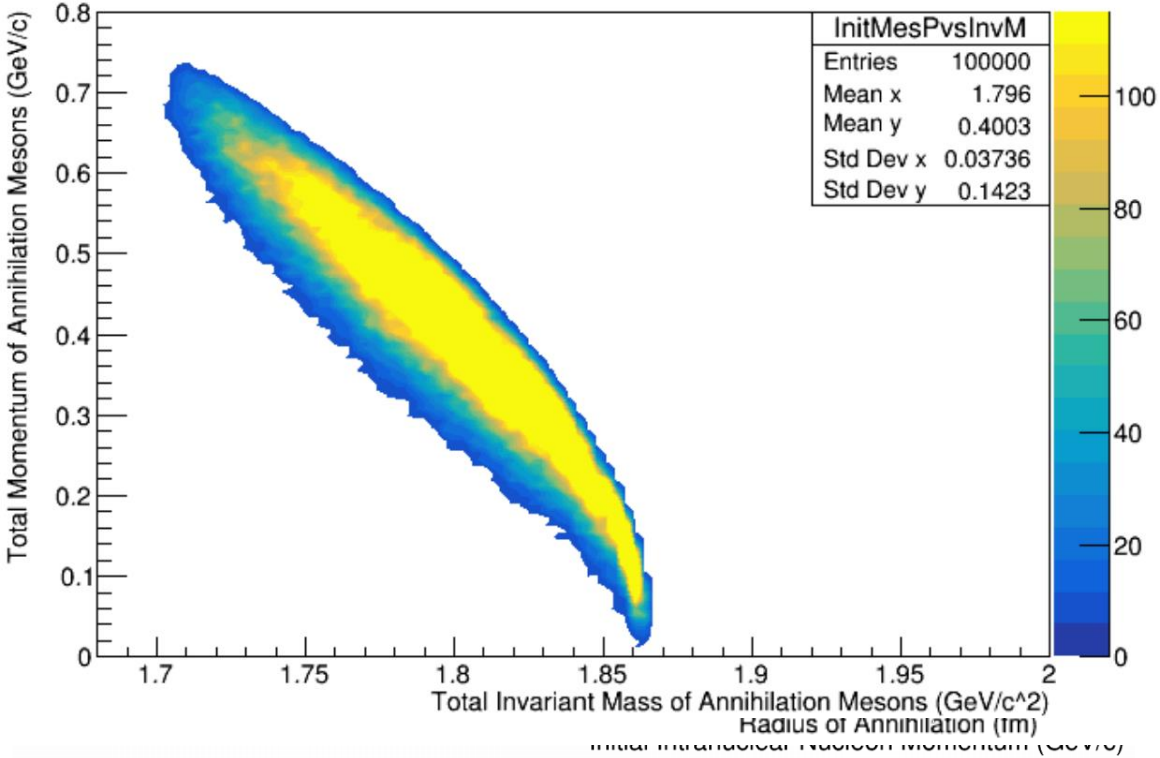
Consider a local Fermi gas nuclear model of Fermi momentum (initial state)



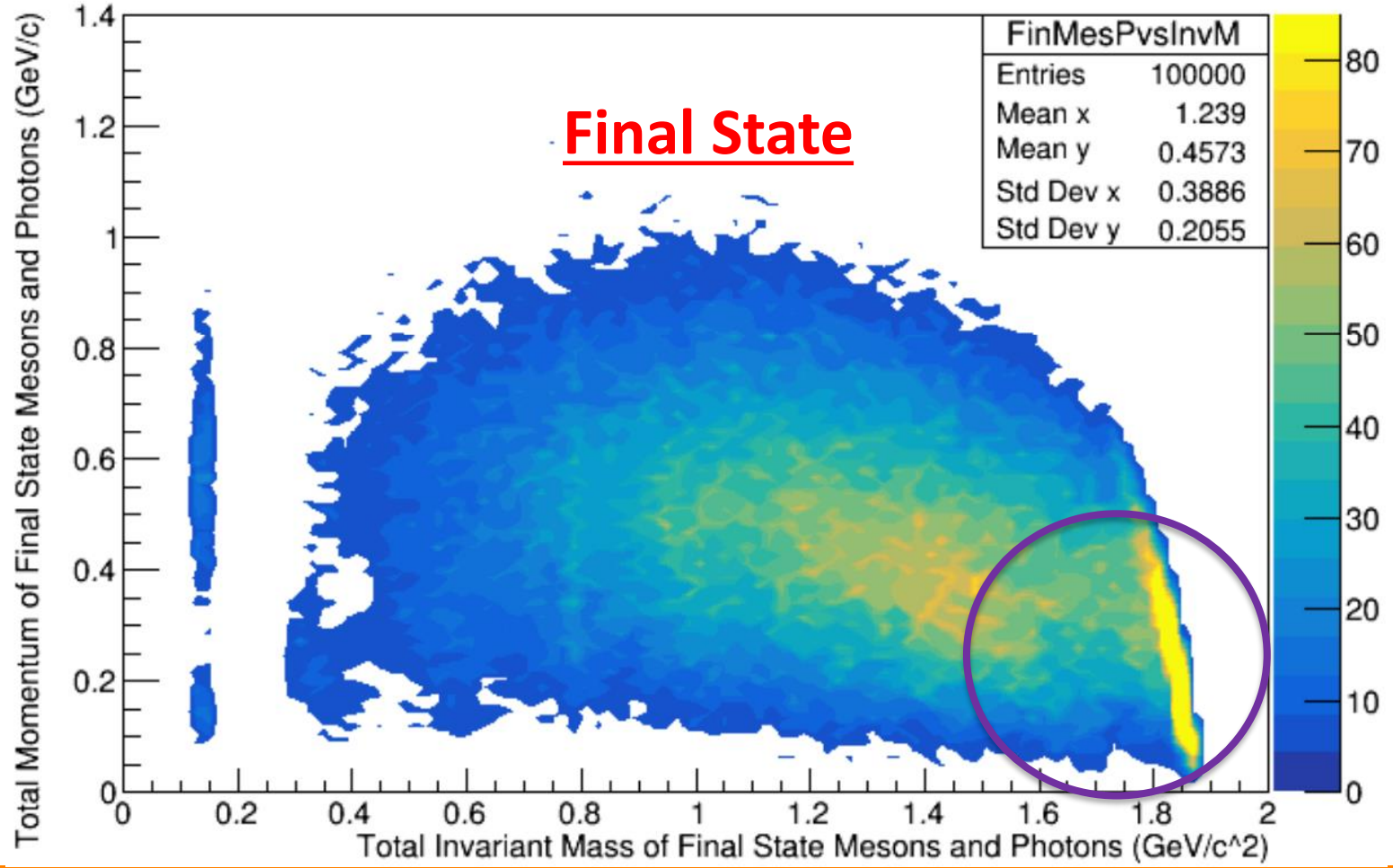
The correlation of radius and momentum has been previously ignored for *all* $n \to \bar{n}$ simulations in *all* experiments

High radii lead to…

- Fewer FSIs, more meson emission
- Lower total momentum (near *ideal case*)



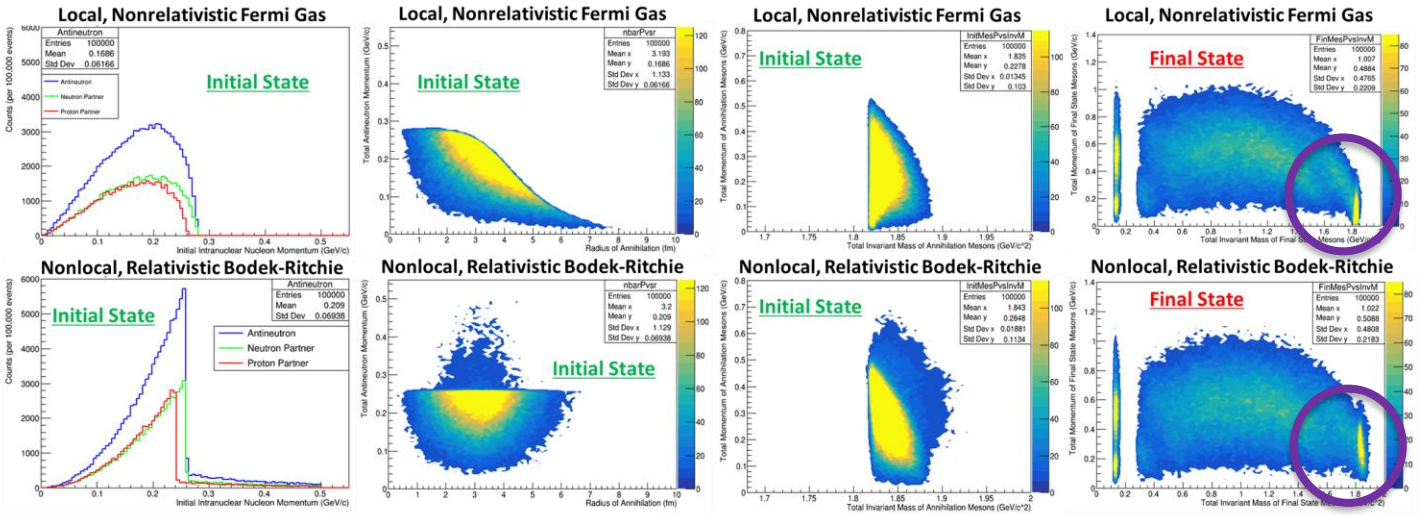
Paryev's distribution


Final State
FinMesPvsInvM
Entries 100000
Mean x 1.239
Mean y 0.4573
Std Dev x 0.3886
Std Dev y 0.2055
Total Momentum of Final State Mesons and Photons (GeV/c)
Total Invariant Mass of Final State Mesons and Photons (GeV/c^2)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
10
20
30
40
50
60
70
80

Model Dependencies in Final State Topologies are Being Investigated

First foray into this study detailed in [our recent PRD]

- Compares many GENIE models to our generator work with **E. S. Golubeva**



Example single nucleon ($p, n, \bar{n}$) Fermi motion momentum distributions are shown for GENIE & Golubeva. These serve as the starting conditions for all annihilation products.

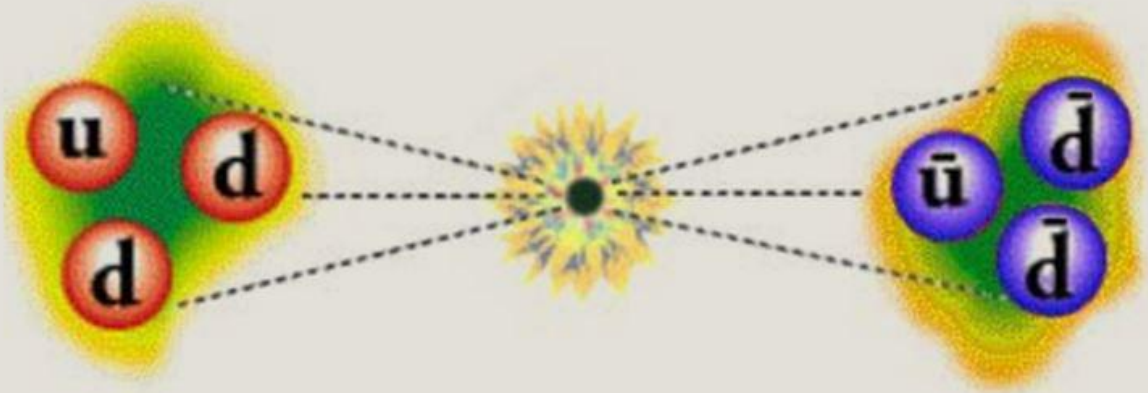
Example $\bar{n}$ momentum vs. radius distributions are shown for GENIE & Golubeva. Annihilation near the nuclear surface may lead to low momentum products with aspherical topologies.

Example initial annihilation product distributions are shown for GENIE & Golubeva. Different initial conditions, & preservation of radial correlations, may effect the final topology.

Example final pionic parameter spaces are shown for GENIE & Golubeva. Some localization of events might imply more complete signal to background separation in automated analyses.

Summary and Conclusions

- DUNE shows potential to reach $\tau_{n\bar{n}} \geq 5.58 \times 10^8 s$ lower limit
- Improvements are sought via…
  - Better reconstruction can hopefully lead to better ROI selection
  - BDT input of CNN PID for better cuts against background
- Iteration over nuclear model configurations underway
  - Will allow us to test stability of CNN/BDT response to various topological differences
    - Effectively determine model systematics
  - Will $S:B$ remain the same independent of the nuclear model configuration?



$$n \longrightarrow \overline{n}$$

[Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part 1]

ACFI WORKSHOP ON $\Delta\mathcal{B} = 2$

Associated Letter of Interest

[$\Delta\mathcal{B} = 2$: A state of the Field, and Looking Forward]